METHODS OF SUPPLYING ENERGY TO AN ENERGY BUS IN A HYBRID ELECTRIC VEHICLE, AND APPARATUSES, MEDIA AND SIGNALS FOR THE SAME

FIELD OF THE INVENTION

The present invention relates to vehicles, and more particularly to methods, apparatuses, media and signals for supplying energy to an energy bus in a hybrid electric vehicle.

BACKGROUND OF THE INVENTION

An electric or hybrid electric vehicle typically employs electric traction motors connected to drive wheels of the vehicle. The traction motors typically receive electrical energy from an energy bus of the vehicle, in response to which the motors apply a torque to the drive wheels, thereby causing the vehicle to accelerate.

In a "series" hybrid electric vehicle, there are typically two available power sources to supply energy to the traction motors to drive the vehicle: an auxiliary power unit or other energy generating device, and an energy storage system.

The auxiliary power unit typically converts another form of energy into electrical energy which it supplies to the energy bus, but is usually not capable of drawing electrical energy from the energy bus and converting it into another form for storage. For example, the auxiliary power unit often includes an internal combustion engine coupled to an electrical generator, for converting mechanical energy derived from the chemical combustion of gasoline (or other hydrocarbons or other fuels) into electrical energy. More recently, fuel cells for generating electrical energy from other chemical

processes such as oxidation of hydrogen for example, have been used as auxiliary power units.

The energy storage system (ESS) typically includes a system capable of both supplying electrical power to energy bus when needed, and capable of receiving surplus electrical energy from the energy bus and storing such energy for future use. For example, the ESS often includes a battery or a set of batteries, or a capacitor bank. When the auxiliary power unit is not operating (or is not supplying sufficient electrical energy to meet the current demands of the vehicle), the ESS will be called upon to supply stored electrical energy to the energy bus in order to drive the traction motors and other electrical devices of the vehicle. Conversely, when the combustion engine or other auxiliary power unit is operating, it often supplies more electrical energy to the energy bus than is required to operate the traction motors to propel the vehicle and to operate other electrical devices of the vehicle, in which case the ESS may draw a charging current from the energy bus in order to store the surplus energy for future use.

In addition to storing such surplus energy from the auxiliary power unit, the energy storage system may also receive and store surplus electrical energy produced during regenerative braking of the vehicle. In this regard, the traction motors may be used as a regenerative braking system for braking the vehicle, by discontinuing the supply of electrical power to the traction motors while leaving the traction motors fully or partially engaged with the drive wheels. During such regenerative braking, the momentum of the vehicle and resulting forced rotation of the drive wheels causes a corresponding forced rotation of the electric traction motors, which act as generators driven by the drive wheels. Effectively, the electric traction motors serve to decelerate the vehicle by converting its kinetic energy into electrical energy which is supplied back to the energy bus. During regenerative braking, the amount of electrical energy supplied to the energy bus by the regenerative braking system typically significantly exceeds the instantaneous electrical energy needs of the

vehicle, because the largest electrical loads, namely, the traction motors themselves, have ceased drawing energy and are now supplying significant amounts of electrical energy back to the energy bus. Therefore, regenerative braking typically produces a significant amount of surplus electrical energy that can be stored by the energy storage system.

Thus, in a series hybrid electric vehicle, there are typically two energy sources capable of supplying surplus electrical energy to charge the energy storage system: the auxiliary power unit, and the traction motors acting as a regenerative braking system.

However, the ability of the energy storage system to safely receive and store energy is typically limited by a number of factors, such as its state of charge, its temperature, its age, and its previous operating conditions, for example. Exceeding the charge acceptance limit of the energy storage system may lead to over-voltage conditions, potentially damaging the energy storage system, and also potentially damaging other electronic components connected to the energy bus.

Therefore, to the extent that the auxiliary power unit and the regenerative braking system may produce surplus electrical energy (i.e., energy in excess of the current electrical needs of the vehicle), if such surplus electrical energy exceeds the amount of energy the energy storage system can safely store, the energy storage system and other electric and/or electronic components of the vehicle may be damaged.

A number of systems have been proposed for monitoring and controlling electrical energy generated by a regenerative braking system and/or an auxiliary power unit, for various purposes. One such system involves detecting a voltage generated by the regenerative braking system, detecting a voltage generated by a generator coupled to an internal combustion engine, and reducing the amount of regenerative braking if the regenerative voltage exceeds the generator's voltage, in order to protect an internal combustion

engine against over-speed operation. It is noted that reducing regenerative braking output in favor of the generator output disadvantageously reduces vehicle efficiency.

More significantly, existing systems tend to be reactionary in nature, and often cannot prevent short but damaging voltage spikes from occurring. For example, in a conventional series hybrid electric vehicle, if a user of the vehicle is accelerating at full throttle, the auxiliary power unit will be operating at full power, supplying its maximum amount of electrical energy to the energy bus in order to power the traction motors. If the user then brakes suddenly, the traction motors suddenly switch from operating as a large energy drain to operating as a generator, supplying a large supply of electrical energy to the energy bus, while at the same time, the auxiliary power unit will still initially be operating at or near full power, not having had sufficient time to reduce its output. The resulting surplus electrical energy supplied to the energy bus by the traction motors and the auxiliary power unit typically largely exceeds the charge acceptance of the energy storage system, and the resulting over-voltage condition on the energy bus not only has a detrimental effect on the service life of the energy storage system, but is also potentially damaging to other electronic and/or electrical devices connected to the energy bus. A conventional reactionary system may detect and respond to the over-voltage condition, but typically not until after such potentially damaging voltage spikes have occurred.

Accordingly, there is a need for an improved way of supplying energy in a hybrid electric vehicle.

SUMMARY OF THE INVENTION

The present invention addresses the above need by providing, in accordance with one aspect of the invention, a method of supplying energy to an energy bus in communication with an energy generating device and with a

regenerative braking system in a hybrid electric vehicle. The method includes controlling power supplied by the energy generating device to the energy bus, in response to a braking signal indicative of user brake actuation.

By controlling power supplied by the energy generating device in response to the braking signal, the power may be controlled proactively, to prevent an over-voltage condition from occurring, in contrast with previous systems that react to an over-voltage condition that is in the process of occurring.

Controlling power preferably includes controlling power supplied by an auxiliary power unit (APU) of the vehicle. This may include controlling a current supplied by a generator, or may include controlling a current supplied by a fuel cell, for example.

Controlling preferably includes commencing the controlling no later than a time at which the regenerative braking system of the vehicle commences supplying energy to the energy bus.

Controlling preferably includes reducing the power supplied by the energy generating device to the energy bus. If so, the method may further include increasing power supplied by the regenerative braking system of the vehicle to the energy bus, while reducing the power supplied by the energy generating device to the energy bus.

Thus, in such an embodiment, regenerative braking energy is effectively favored over energy supplied by the energy generating device, thereby improving the efficiency of the vehicle by increasing the amount of energy recovered from the vehicle's kinetic energy while decreasing fuel consumption.

Increasing power may include increasing a regenerative braking torque applied by the regenerative braking system until a desired regenerative braking torque is achieved.

The method may further include identifying a total desired braking torque in response to the braking signal. The method may also include identifying a maximum available regenerative braking torque. In this case, the method preferably further includes identifying a maximum desired regenerative braking torque, in response to the total desired braking torque and the maximum available regenerative braking torque.

Identifying the maximum desired regenerative braking torque may include setting the maximum desired regenerative braking torque equal to the lesser of: (a) the total desired braking torque; (b) the maximum available regenerative braking torque; and (c) a torque equivalent of a desired current drain from the energy bus, the desired current drain including a desired charging current for charging an energy storage system (ESS) in communication with the energy bus.

Controlling may include setting a desired power output of the energy generating device, in response to the maximum desired regenerative braking torque. Setting the desired power output may include setting a desired current level of an auxiliary power unit (APU) of the vehicle, which may include setting the desired current level equal to the lesser of: (a) a present desired current level of the APU; and (b) a desired current drain from the energy bus including a desired charging current for charging an energy storage system (ESS) in communication with the energy bus, minus a current equivalent of the maximum desired regenerative braking torque.

The method may further include setting a present desired regenerative braking torque of a regenerative braking system of the vehicle, in response to the maximum desired regenerative braking torque and the power supplied by the energy generating device to the energy bus. This may include setting the present desired regenerative braking torque equal to the lesser of: (a) the maximum desired regenerative braking torque; and (b) a torque equivalent of: (i) a desired current drain from the energy bus, the desired current drain

including a desired charging current for charging an energy storage system (ESS) in communication with the energy bus; minus (ii) an actual current supplied by the energy generating device to the energy bus.

The method may further include identifying, as the desired charging current, a maximum allowable charging current for charging the ESS.

The method may further include setting a friction braking torque of a friction braking system of the vehicle. This may include setting the friction braking torque equal to a difference between the present desired regenerative braking torque and the total desired braking torque. Thus, friction brakes may be used to complement the regenerative braking system if required, in order to provide adequate total braking torque to provide a consistent and predictable brake feel.

Controlling preferably includes controlling energy contributions onto the energy bus from the energy generating device and from a regenerative braking system of the vehicle respectively, to prevent the contributions from exceeding a desired total energy contribution.

In accordance with another aspect of the invention, there is provided an apparatus for supplying energy to an energy bus in communication with an energy generating device and with a regenerative braking system in a hybrid electric vehicle. The apparatus includes a processor circuit configured to control power supplied by the energy generating device to the energy bus, in response to a braking signal indicative of user brake actuation.

The processor circuit may be programmed or configured to perform the various methods described herein.

In accordance with another aspect of the invention, there is provided a system including an apparatus as described above and further including the energy generating device, the energy generating device being in communication with the processor circuit and with the energy bus.

The energy generating device may include an auxiliary power unit (APU) of the vehicle. The APU may include a generator, or may include a fuel cell, for example.

The system may further include the energy bus.

The system may further include the regenerative braking system, the regenerative braking system being in communication with the processor circuit and with the energy bus. The processor circuit may be configured to increase power supplied by the regenerative braking system to the energy bus, while reducing the power supplied by the energy generating device to the energy bus.

The system may further include an energy storage system (ESS) in communication with the energy bus.

In accordance with another aspect of the invention, there is provided an apparatus for supplying energy to an energy bus in communication with energy generating means and with regenerative braking means in a hybrid electric vehicle. The apparatus includes means for receiving a braking signal indicative of user brake actuation, and means for controlling power supplied by the energy generating means to the energy bus, in response to the braking signal.

The apparatus may further include means for performing any of the functions or methods described herein. Such means may include the aforementioned means or may include additional means for performing such functions.

In accordance with another aspect of the invention, there is provided a system including an apparatus as described above and further including the energy generating means for generating the power supplied by the energy generating means to the energy bus, the energy generating means being in communication with the means for reducing power and with the energy bus.

The energy generating means may include an auxiliary power unit (APU) of the vehicle.

The system may further include the regenerative braking means for regeneratively braking the vehicle, the regenerative braking means being in communication with the energy bus.

The system may further include an energy storage means for storing energy, in communication with the energy bus.

In accordance with another aspect of the invention, there is provided a computer readable medium providing codes for directing a processor circuit to control power supplied by an energy generating device to an energy bus in communication with the energy generating device and with a regenerative braking system in a hybrid electric vehicle, in response to a braking signal indicative of user brake actuation.

In accordance with another aspect of the invention, there is provided a signal including code segments for directing a processor circuit to control power supplied by an energy generating device to an energy bus in communication with the energy generating device and with a regenerative braking system in a hybrid electric vehicle, in response to a braking signal indicative of user brake actuation.

In accordance with another aspect of the invention, there is provided a method of supplying energy to an energy bus in a hybrid electric vehicle. The method includes controlling energy contributions onto the energy bus from an energy generating device and from a regenerative braking system respectively, to prevent the contributions from exceeding a desired total energy contribution.

Controlling preferably includes reducing power supplied by the energy generating device to the energy bus.

More particularly, controlling preferably includes reducing power supplied by the energy generating device to the energy bus, while increasing power supplied by the regenerative braking system to the energy bus. Increasing power preferably includes increasing a regenerative braking torque applied by the regenerative braking system until a desired regenerative braking torque is achieved.

The method may further include identifying a maximum desired regenerative braking torque to be applied by the regenerative braking system. If so, controlling preferably includes setting a desired energy contribution of the energy generating device, in response to the maximum desired regenerative braking torque.

The method may further include setting a present desired regenerative braking torque of the regenerative braking system, in response to the maximum desired regenerative braking torque and an actual energy contribution supplied by the energy generating device to the energy bus.

Controlling preferably includes controlling power supplied by the energy generating device to the energy bus, in response to a braking signal indicative of user brake actuation.

In accordance with another aspect of the invention, there is provided an apparatus for supplying energy to an energy bus in a hybrid electric vehicle. The apparatus includes a processor circuit configured to control energy contributions onto the energy bus from an energy generating device and from a regenerative braking system respectively, to prevent the contributions from exceeding a desired total energy contribution.

The processor circuit may be further programmed or configured to perform the various methods described herein.

In accordance with another aspect of the invention, there is provided an apparatus for supplying energy to an energy bus in a hybrid electric vehicle.

The apparatus includes first means for controlling a first energy contribution onto the energy bus from energy generating means, and second means for controlling a second energy contribution onto the energy bus from regenerative braking means. The first and second means for controlling cooperate to prevent the contributions from exceeding a desired total energy contribution.

The apparatus may further include means for performing the various functions or methods described herein. Such means may include the aforementioned means or may include additional means for performing such functions.

In accordance with another aspect of the invention, there is provided a computer readable medium providing codes for directing a processor circuit to control energy contributions onto an energy bus in a hybrid electric vehicle from an energy generating device and from a regenerative braking system respectively, to prevent the contributions from exceeding a desired total energy contribution.

In accordance with another aspect of the invention, there is provided a signal including code segments for directing a processor circuit to control energy contributions onto an energy bus in a hybrid electric vehicle from an energy generating device and from a regenerative braking system respectively, to prevent the contributions from exceeding a desired total energy contribution.

Other aspects and features of the present invention will become apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate embodiments of the invention,

Figure **1**   is a block diagram of an apparatus for supplying energy to an energy bus in communication with an energy generating device and with a regenerative braking system in a hybrid electric vehicle, according to a first embodiment of the invention;

Figure **2**   is a partial schematic illustration of an apparatus for supplying energy to an energy bus in communication with an energy generating device and with a regenerative braking system in a hybrid electric vehicle, according to a second embodiment of the invention, with some components and connections omitted for ease of illustration;

Figure **3**   is a partial schematic illustration of an apparatus for supplying energy to an energy bus in communication with an energy generating device and with a regenerative braking system in a hybrid electric vehicle, according to a third embodiment of the invention, with some components and connections omitted for ease of illustration;

Figure **4**   is a block diagram illustrating communication among a processor circuit, the energy generating device, the regenerative braking system, and various other components of the hybrid electric vehicle shown in Figure **2**;

Figure **5**   is a block diagram illustrating the processor circuit of the apparatus shown in Figure **2**; and

Figure **6**   is a flowchart of an energy supply routine executed by the processor circuit shown in Figure **5**.

DETAILED DESCRIPTION

Referring to Figure **1**, an apparatus according to a first embodiment of the invention is shown generally at **20**. In this embodiment, the apparatus is used for supplying energy to an energy bus **22** in communication with an energy generating device **24** and with a regenerative braking system **26** in a hybrid electric vehicle (not shown). The apparatus **20** includes a processor circuit **28**, configured to control power supplied by the energy generating device **24** to the energy bus **22**, in response to a braking signal **30** indicative of user brake actuation.

In this embodiment, the processor circuit **28** is configured to control energy contributions onto the energy bus **22** from the energy generating device **24** and from the regenerative braking system **26** respectively, to prevent the contributions from exceeding a desired total energy contribution.

Referring to Figure **2**, a system according to a second embodiment of the invention is shown generally at **38**. In this embodiment, the system **38** includes an apparatus **40** for supplying energy to an energy bus **42** in communication with an energy generating device shown generally at **44** and with a regenerative braking system shown generally at **46**, in a hybrid electric vehicle **48**. In this embodiment, the apparatus **40** includes a processor circuit **50** configured to control power supplied by the energy generating device **44** to the energy bus **42**, in response to a braking signal **52** indicative of user brake actuation. In this embodiment, the processor circuit **50** is also configured to control energy contributions onto the energy bus **42** from the energy generating device **44** and from the regenerative braking system **46** respectively, to prevent the contributions from exceeding a desired total energy contribution.

In this embodiment, the hybrid electric vehicle **48** includes a series hybrid electric vehicle. The regenerative braking system **46** is in communication with the processor circuit **50** and with the energy bus **42**. More particularly, in this embodiment, the regenerative braking system **46** includes first and second traction motors **54** and **56**, each in communication with the energy bus **42**. The traction motors **54** and **56** are engageable with respective drive wheels **58** and **60**, and serve to propel or accelerate the vehicle **48** by applying torque to the drive wheels **58** and **60** in response to electrical energy received by the traction motors **54** and **56** from the energy bus **42**. Conversely, during regenerative braking, the traction motors act as generators driven by the drive wheels, thereby effectively converting the kinetic energy of the vehicle into electrical energy supplied to the energy bus. In this embodiment, the traction motors **54** and **56** include traction motors manufactured by Unique Mobility, Inc. of Golden, Colorado, USA. Alternatively, other types of traction motors may be substituted.

In the present embodiment, for ease of illustration, the traction motors **54** and **56** of the regenerative braking system **46** are shown and described only in connection with the drive wheels **58** and **60**, which in this embodiment are the front wheels of the hybrid electric vehicle **48**. Alternatively, however, such traction motors may be provided in connection with all wheels of the vehicle, thus providing for all wheel drive and for regenerative braking energy recovery from all wheels of the vehicle. Alternatively, a single such traction motor may be provided for each axle of the vehicle rather than for each wheel, if desired. More generally, other types of propulsion and regenerative braking systems may be substituted if desired.

In this embodiment, there are two energy sources operable to supply electrical energy to the traction motors **54** and **56** via the energy bus **42**, namely, the energy generating device **44** and an energy storage system (ESS) **62**.

Referring to Figure **2**, in this embodiment the energy generating device **44** is in communication with the processor circuit **50** and with the energy bus **42**. In the present embodiment, the energy generating device **44** includes an auxiliary power unit (APU) **64** of the vehicle. More particularly, in this embodiment the APU **64** includes a generator **66** coupled to a prime mover **68**. The prime mover **68** supplies mechanical energy to the generator **66**, which converts such energy into electrical energy, which it then supplies to the energy bus **42**. Thus, in the present embodiment, the processor circuit **50** is configured to control the power supplied by the energy generating device to the energy bus by controlling power supplied by the APU **64** of the vehicle **48**, or more particularly, by controlling a current supplied by the generator **66** to the energy bus.

In this embodiment, the prime mover **68** includes an internal combustion engine. Alternatively, the generator **66** may be coupled to other types of prime mover. For example, the generator **66** may be coupled to a turbine.

Referring to Figure **3**, alternatively, the auxiliary power unit **64** may include other means for generating energy. For example, in the alternative embodiment shown in Figure **3**, the auxiliary power unit includes a fuel cell **69**, and the processor circuit **50** is configured to control the power supplied by the energy generating device **44** by controlling a current supplied by the fuel cell **69** to the energy bus **42**.

Referring back to Figure **2**, in the present embodiment, the energy storage system **62** in communication with the processor circuit **50** and with the energy bus **42**. The energy storage system **62** of the present embodiment is operable to supply electrical energy to the energy bus **42**, which may then supply such energy to the traction motors **54** and **56** to accelerate the vehicle **48**. Conversely, when there is a surplus of electrical energy on the energy bus **42**, which may result from excess energy supplied by the auxiliary power unit **64** and/or from regenerative braking energy supplied by the regenerative

braking system **46**, the energy storage system **62** receives and stores such surplus energy for future use. To achieve this, in the present embodiment, the energy storage system **62** includes at least one battery, such as that shown at **70** for example. The ESS **62** further includes an ESS controller **72** for monitoring and regulating the state of charge, temperature and other physical properties of the battery **70**.

In the present embodiment, the energy bus **42** includes a direct current electrical bus. More particularly, in this embodiment the energy bus includes electrical wires rated for high-voltage, high-current applications. For example, in the present embodiment the electrical wires of the energy bus include wires rated for **300** ampères of continuous direct current.

In this embodiment, the energy generating device **44**, the regenerative braking system **46**, the energy storage system **62**, and a plurality of other high voltage loads such as those shown at **74**, for example, are electrically connected in parallel to the energy bus **42**.

The other loads **74** may include other devices of the vehicle **48** requiring a high voltage power supply, such as a power steering system and a heating system, for example. In this embodiment, the other loads **74** further include a step down transformer **76**, for providing a low voltage power supply **78** for use by other low voltage devices of the vehicle **48**, such as a friction braking system **80**, a brake pedal sensor **82** and a speedometer **84**, for example.

In this embodiment, the friction braking system **80** includes a conventional friction braking system such as a hydraulic disk or drum brake system, for example. Alternatively, other types of friction braking systems may be substituted. Alternatively, the friction braking system may be omitted if desired, however, it is strongly preferable that a friction braking system be provided for safety reasons. For example, there may be circumstances in which a user of the vehicle **48** wishes or needs to decelerate with a greater braking torque than the regenerative braking system **46** is providing. In

addition, as the user-requested braking torque is not the only factor influencing the manner in which the processor circuit **50** of the present embodiment controls the applied regenerative braking torque, this further heightens the desirability of a friction braking system to ensure that the desired braking torque is always supplied, for safety reasons. The friction braking system also complements the regenerative braking system **46** in order to provide and maintain a more predictable and consistent brake feel. Although the friction braking system **80** is shown in Figure **2** in connection with a single wheel for illustrative purposes, friction braking components are preferably provided for all of the wheels of the vehicle **48**.

Referring to Figure **4**, in this embodiment, the processor circuit **50** is in communication with a communications network shown generally at **90**. More particularly, in this embodiment, the communications network **90** includes a two wire controller area network (CAN), employing a CAN protocol, to receive communication signals from and transmit control signals to various devices of the hybrid electric vehicle **48**. Alternatively, however, other types of communications networks may be substituted.

More particularly, referring to Figures **2** and **4**, in this embodiment the processor circuit **50** is in communication via the network **90** with the auxiliary power unit **64**, via a control/communications interface **94** thereof. The processor circuit is also in communication with a first current sensor **96** for receiving current detection signals therefrom. More particularly still, the first current sensor **96** measures an electric current supplied by the auxiliary power unit **64** to the energy bus **42**, and transmits signals representing the current measurement onto the network **90** for receipt by the processor circuit **50**.

Similarly, in the present embodiment the processor circuit **50** is also in communication with a voltage sensor **97** for receiving voltage detection signals therefrom. More particularly, the voltage sensor **97** measures a

voltage on the energy bus **42**, and transmits signals representing the voltage measurement onto the network **90** for receipt by the processor circuit.

In this embodiment, the processor circuit **50** is in further communication, via the network **90**, with the energy storage system **62**, via a communications interface **98** thereof.

Similarly, in the present embodiment, the processor circuit **50** is in communication via the network **90** with the regenerative braking system **46**, via a control/communications interface **100** thereof.

Also in this embodiment, the processor circuit **50** is in communication via the network **90** with the other high voltage loads **74** including the transformer **76**, via at least one communications interface **102** thereof. The processor circuit **50** is also in communication with a second current sensor **104** which measures a total electrical current drawn by the other high voltage loads **74** from the energy bus **42**, and which transmits signals representing this drawn current measurement onto the network **90** for receipt by the processor circuit **50**.

Similarly, in this embodiment, the processor circuit **50** is in communication via the network **90** with a plurality of low voltage devices of the vehicle **48**. More particularly, in this embodiment, the processor circuit **50** is in communication with the friction braking system **80** via a control interface **106** thereof, with the brake pedal sensor **82** via a communications interface **105** thereof, and with the speedometer **84** via a communications interface **108** thereof.

In this embodiment, the processor circuit **50** is in further communication via the network **90** with a charging strategy selector **110** via a communications interface **112** thereof. The charging strategy selector **110** selects a particular strategy or method for charging the energy storage system **62**. For example, such selectable strategies may include "fast" charging, also referred to as "opportunistic" charging, in which as much current as possible is used to

charge the energy storage system, subject only to the maximum allowable charging current receivable by the energy storage system. Such a strategy serves to minimize auxiliary power unit transients. Alternatively, a further charging strategy may include "float" charging, whereby the energy storage

5   system **62** is charged at a different level (typically less than the maximum possible permitted charging level) according to an energy storage system charge profile current level determined by a separate controller of the energy storage system **62**. In this embodiment, the charging strategy selector **110** includes a switch that may be actuated by a user of the vehicle **48**, to transmit

10   signals onto the communication network **90** representing either a selection of "fast" charging or of "float" charging, respectively. Alternatively, the selection of charging strategies may be determined automatically if desired.

If desired, the processor circuit **50** may be in further communication with other additional devices of the vehicle **48**, either via the communication network **90**

15   or otherwise.

Referring to Figure **5**, the processor circuit is shown generally at **50**. In this embodiment, the processor circuit **50** includes a microprocessor **120**. Alternatively, other types of processor circuits may be substituted for the microprocessor **120**. More generally, in this specification, the term "processor

20   circuit" is intended to broadly encompass any type of circuit, device or combination of circuits and/or devices capable of performing the functions described herein or equivalent functions, including (without limitation) other types of microprocessors, microcontrollers, other integrated circuits, other types of electrical circuits or combinations of circuits, logic gates or gate

25   arrays, or programmable devices of any sort, either alone or in combination with other such circuits or devices located at the same location or remotely from each other, for example. Additional types of processor circuits will be apparent to those ordinarily skilled in the art upon review of this specification, and substitution of any such other types of processor circuits is considered

not to depart from the scope of the present invention as defined by the claims appended hereto.

In this embodiment, the microprocessor **120** is in communication with a plurality of memory devices, including a non-volatile memory **122**, a random access memory (RAM) **124**, and a media interface **126**.

In this embodiment, the non-volatile memory **122** is used to store various routines executable by the microprocessor **120**, including an energy supply routine **128**. Thus, as discussed in greater detail below in connection with the energy supply routine **128**, in this embodiment the non-volatile memory **122** acts as a computer readable medium providing codes for directing the processor circuit **50** to control power supplied by the energy generating device **44** to the energy bus **42** in response to the braking signal **52** indicative of user brake actuation, and similarly, acts as a computer readable medium providing codes for directing the processor circuit to control the energy contributions onto the energy bus from the energy generating device and from the regenerative braking system respectively, to prevent the contributions from exceeding a desired total energy contribution. In this embodiment, the non-volatile memory **122** cooperates with the microprocessor **120** to produce a signal **123** comprising code segments for directing the processor circuit **50** to perform the functions of the energy supply routine **128**. Alternatively, however, other ways of generating such signals may be substituted. In this embodiment, the non-volatile memory **122** includes an erasable, re-writable computer readable medium, such as an electrically erasable programmable read only memory (EEPROM) or a FLASH memory, for example. Alternatively, other types of computer readable media may be substituted for the non-volatile memory **122**, such as removable media insertable into the media interface **126**, for example.

In the present embodiment, the non-volatile memory **122** also stores a plurality of look-up maps for use by the microprocessor in executing the

energy supply routine **128**, including a desired braking torque look-up map **130**, a maximum available regenerative braking torque look-up map **132**, a maximum charging current look-up map **133**, and first and second traction motor efficiency look-up maps **134** and **135**. In this embodiment, the desired braking torque look-up map **130** includes fields for vehicle speed, brake pedal position, and desired braking torque, and thus allows for fast output of a desired braking torque corresponding to vehicle speed and brake pedal position input variables. If desired, further input variable fields may be provided, such as a brake pedal position rate of change field, for example. Similarly, in this embodiment the maximum available regenerative braking torque look-up map **132** includes fields for traction motor rotational speed, traction motor temperature, and maximum available regenerative braking torque, and thus allows for fast output of a maximum available regenerative braking torque corresponding to traction motor rotational speed and temperature input variables. Also in this embodiment, the maximum charging current look-up map **133** includes fields for state of charge, temperature, and maximum allowable charging current, to allow fast identification of the latter in response to the former input variables. In the present embodiment the first traction motor efficiency look-up map **134** includes fields for traction motor torque, traction motor rotational speed, and traction motor efficiency, to allow fast identification of the latter in response to the former two input variables. Similarly, the second traction motor efficiency look-up map **135** includes fields for traction motor-generated power, traction motor rotational speed, and traction motor efficiency, to allow fast identification of the latter in response to the former two input variables.

It will be appreciated that the specific contents of the desired braking torque look-up map **130**, the maximum available regenerative braking torque look-up map **132**, the maximum charging current look-up map **133** and the efficiency look-up maps **134** and **135** are dependent upon the properties of the particular vehicle to which the look-up maps relate. In this embodiment, the

maximum available regenerative braking torque look-up map **132** and the efficiency look-up maps **134** and **135** are provided by the manufacturer of the traction motors **54** and **56**, which in this embodiment is Unique Mobility, Inc. of Golden, Colorado, USA. More generally, the identification of the specific

5 contents of the various look-up maps corresponding to a particular vehicle would be well within the abilities of one ordinarily skilled in the art.

In this embodiment, the energy supply routine **128** programs or configures the microprocessor **120** to define various registers in the RAM **124**, including the following: a vehicle speed register **136**; a brake pedal sensor register **138**; a

10 total desired braking torque register **140**; a traction motor properties register **142**; an energy storage system properties register **143**; a maximum available regenerative braking torque register **144**; a maximum allowable charging current register **146**; an energy storage system setpoint register **148**; a charging strategy flag register **150**; a desired charging current register **152**; an

15 other loads register **153**; an energy bus voltage register **154**; a traction motor efficiency register **155**; a desired current drain register **156** including a torque sub-field **157**; a maximum desired regenerative braking torque register **158** including a current sub-field **159**; a desired APU power output register **160**; an actual APU power output register **162**; a present desired regenerative braking

20 torque register **164**; and a friction braking torque register **166**. These registers and their respective contents are discussed in greater detail further below, in the context of the energy supply routine **128**.

In this embodiment, the media interface **126** includes a laser disk reader, which employs a laser to read information from a disk **170**, which may include

25 a DVD or a CD formatted disk, for example. Alternatively, or in addition, the media interface **126** may include a floppy diskette drive for receiving information from a floppy diskette **172**, for example. Alternatively, any other type of computer readable media may be substituted for the disk **170** or the diskette **172**, and appropriate corresponding media readers may be

30 substituted for the media interface **126**. Such computer readable media may

be employed instead of, or in addition to, the non-volatile memory **122**, in order to provide or update the various routines and/or the look-up maps stored in the non-volatile memory **122**.

Referring to Figures **4** and **5**, in this embodiment the microprocessor **120** is in further communication with an input interface **180** and with an output interface **182**, for receiving communication signals from various devices of the vehicle **48**, and for transmitting control signals to such devices, respectively. To achieve this, in the present embodiment the input and output interfaces **180** and **182** are in communication with the communications network **90** shown in Figure **4**. The input interface **180** and the output interface **182** may include separate interfaces such as those shown in Figure **5**, for example, or alternatively, may include a single input/output ("I/O") interface.

In this embodiment, the input interface **180** receives, from the communications network **90**, signals from the various devices connected thereto (or their respective interfaces), including signals from the first current sensor **96**, from the auxiliary power unit **64**, from the second current sensor **104**, from the brake pedal sensor **82**, from the energy storage system **62**, from the regenerative braking system **46**, from the speedometer **84** and from the charging strategy selector **110**. Such signals are relayed to the microprocessor **120**.

In this embodiment, the output interface **182** transmits control signals from the microprocessor **120** via the communications network **90**, to the interfaces **94**, **100**, **106** and **98** of the auxiliary power unit **64**, the regenerative braking system **46**, the friction braking system **80** and the energy storage system **62**, respectively.

Referring to Figure **5**, in the present embodiment the microprocessor **120** is in further communication with an external communications interface **184**. The external communications interface **184** may be used to enable the microprocessor **120** to communicate with devices outside the hybrid electric

vehicle **48**, and may include a wireless communications interface for communicating with a network such as the internet, for example. If desired, the external communications interface **184** may be employed to enable an external control device to transmit control signals to the microprocessor **120** to

5   cause it to alter or update the routines and look-up maps stored in the non-volatile memory **122**. Similarly, the external communications interface **184** may be used to enable an external control device to transmit to the processor circuit a control signal such as the signal **123**, the signal including code segments for directing the processor circuit to carry out functions similar to

10   those of the energy supply routine **128**, or other functions, if desired.

Referring to Figures **4**, **5** and **6**, the energy supply routine is shown generally at **128** in Figure **6**. Generally, the energy supply routine **128** programs or configures the processor circuit **50** to control power supplied by the energy generating device **44** to the energy bus **42**, in response to the braking signal

15   **52** indicative of user brake actuation. The energy supply routine **128** of the present embodiment also configures the processor circuit **50** to control the energy contributions onto the energy bus **42** from the energy generating device **44** and from the regenerative braking system **46** respectively, to prevent the contributions from exceeding a desired total energy contribution.

20   Referring to Figures **2**, **4**, **5** and **6**, the energy supply routine **128** begins with a first block **200** of codes which directs the processor circuit **50** to receive a braking signal indicative of user brake actuation. More particularly, block **200** directs the processor circuit to monitor the braking signal **52** received from the brake pedal sensor **82** via the communications network **90**, to determine

25   whether the braking signal is indicative of actuation by a user of a brake pedal of the vehicle to which the brake pedal sensor **82** is connected. Various ways of monitoring such signals and determining whether brake actuation has occurred would be readily apparent to those ordinarily skilled in the art upon review of this specification. For example, in the present embodiment, the

30   brake pedal sensor **82** generates signals indicative of a position of the brake

pedal of the vehicle **48**, and block **200** directs the processor circuit to periodically receive such signals from the brake pedal sensor **82**, and to maintain, in the brake pedal sensor register **138**, a present brake pedal position value produced in response to the signals presently received from the brake pedal sensor **82** via the network **90**, and a previous brake pedal position value produced in response to the signals received from the brake pedal sensor **82** at the time of the most recent previous brake pedal position determination. If both the present and previous brake pedal position values stored in the brake pedal sensor register **138** are equal to zero, there is no need to execute the remainder of the energy supply routine **128**, as the user is not presently depressing the brake pedal, and the energy supply routine **128** will have executed at least once with a total desired braking torque of zero, allowing both regenerative and friction braking to reset to zero. Conversely, if at least one of the present brake pedal position value and the previous brake pedal position value is not equal to zero, then block **200** directs the processor circuit **50** to respond to the signals received from the brake pedal sensor **82** by executing the remainder of the energy supply routine **128**, and in this regard, the processor circuit is directed to block **210** discussed below. Alternatively, other ways of determining whether a braking signal has been received may be substituted.

In this embodiment, block **210** directs the processor circuit **50** to identify a total desired braking torque in response to the braking signal **52** received from the brake pedal sensor **82**. To achieve this, block **210** directs the processor circuit to receive signals from the speedometer **84** via the network **90** representing the current speed of the vehicle, and to store a value representing this current vehicle speed in the vehicle speed register **136** of the RAM **124**. Block **210** then directs the processor circuit to use the present vehicle speed value stored in the vehicle speed register **136**, and the present brake pedal position value stored in the brake pedal sensor register **138**, to locate and address a corresponding record in the desired braking torque look-

up map **130** stored in the non-volatile memory **122**. Upon locating the corresponding record in the desired braking torque look-up map, block **210** directs the processor circuit to copy the contents of a total desired braking torque field (not shown) of the record into the total desired braking torque

5   register **140** of the RAM **124**. Alternatively, however, other ways of determining the total desired braking torque in response to a braking signal may be substituted. For example, if desired, the present and previous brake pedal position values stored in the brake pedal sensor register **138** may be used to calculate a rate of change of the brake pedal position, representing

10   the speed with which the user has depressed the brake pedal, this rate of change value may be used as an additional variable to address the desired braking torque look-up map **130**, in order to effectively provide a brake assist function, to provide greater braking torque in response to a faster or more urgent actuation of the brake pedal by the user. Or, as a further example, the

15   desired braking torque may be calculated from a predefined formula.

Referring to Figures **2**, **4**, **5** and **6**, block **220** then directs the processor circuit **50** to identify the maximum available regenerative braking torque that could presently be provided by the regenerative braking system **46** of the vehicle **48**. In this regard, referring back to Figure **2**, it will be appreciated that if the

20   vehicle **48** is in motion and the traction motors **54** and **56** cease to draw energy from the energy bus **42** to rotate the drive wheels **58** and **60** while remaining engaged with the drive wheels, the forward momentum of the vehicle **48** causes the drive wheels **58** and **60** to continue rotating, thus forcing the traction motors **54** and **56** to rotate. The traction motors thus act

25   as generators driven by the drive wheels, supplying energy to the energy bus **42**, by converting the vehicle's kinetic energy into electricity. Block **220** directs the processor circuit **50** to identify the maximum regenerative braking torque that the traction motors **54** and **56** could presently apply to the drive wheels **58** and **60** in order to decelerate the vehicle **48**. To achieve this, block

30   **220** directs the processor circuit to receive signals from the regenerative

braking system **46** via its communications interface **100** and the network **90**, representing the present rotational speeds and the temperatures of the traction motors **54** and **56**, and to store these values in the traction motor properties register **142** of the RAM **124**. Block **220** then directs the processor circuit to use these rotational speed and temperature values to locate and address a corresponding record in the maximum available regenerative braking torque look-up map **132** in the non-volatile memory **122**. Upon locating such a record, block **220** directs the processor circuit to copy the contents of a maximum available regenerative braking torque field (not shown) of the addressed record of the look-up map **132** into the maximum available regenerative braking torque register **144** of the RAM **124**.

Block **230** then directs the processor circuit **50** to identify a desired charging current for charging the energy storage system **62** of the vehicle **48**. In the present embodiment, the manner in which the desired charging current is determined depends upon whether the charging strategy selector **110** indicates a "fast" (or "opportunistic") charging strategy, or whether it indicates a "float" charging strategy. In this regard, block **230** directs the processor circuit to receive a signal from the charging strategy selector **110** via the network **90**, and to store a corresponding value in the charging strategy flag register **150**, representing either a fast or a float charging strategy.

If the charging strategy flag register **150** contents are set active to indicate fast charging, block **230** directs the processor circuit to identify, as the desired charging current, a maximum allowable charging current for charging the energy storage system **62**. To achieve this, block **230** directs the processor circuit **50** to receive signals from the ESS **62** via its interface **98** and the network **90**, indicating a maximum allowable charging current value calculated by the ESS controller **72**, and further directs the processor circuit to store this value in the maximum allowable charging current register **146**. In this regard, in the present embodiment the ESS controller **72** monitors the state of charge and the temperature of the at least one battery **70**, in response to which it

calculates the maximum allowable charging current that can be applied to the at least one battery **70** without exceeding a predetermined maximum battery voltage, and transmits signals representing this maximum allowable charging current onto the network **90** for receipt by the processor circuit **50**.

5 Alternatively, if desired, the maximum allowable charging current may be calculated by the processor circuit **50**, for example, by receiving signals representing the state of charge and temperature of the at least one battery **70** and storing such values in the ESS properties register **143**, then using such values to locate and address a corresponding record in the maximum

10 charging current look-up map **133**, and copying the contents of a maximum allowable charging current field (not shown) of the addressed record to the maximum allowable charging current register **146** and the desired charging current register **152**. As a further alternative, if desired, a control loop may be implemented to apply a correction to the maximum allowable charging

15 current. For example, once the maximum allowable charging current has been initially determined by either the processor circuit **50** or the ESS controller **72** at block **230**, and has been actually applied to the ESS **62** as a result of the execution of blocks **260** and **270** discussed below, the battery voltage may be measured by the ESS controller **72** while the maximum

20 allowable charging current is being applied, and if the battery voltage is less than the known maximum battery voltage, the maximum allowable charging current may be increased until the battery voltage equals the maximum battery voltage. Irrespective of how the maximum allowable charging current register **146** contents are obtained, if the charging strategy flag register **150**

25 contents are set active to indicate fast charging, block **230** directs the processor circuit **50** to copy the contents of the maximum allowable charging current register **146** to the desired charging current register **152**.

Alternatively, if the contents of the charging strategy flag register **150** are inactive to indicate a float charging strategy, block **230** directs the processor

30 circuit **50** to identify the desired charging current for charging the ESS **62**, by

receiving signals from the energy storage system **62** via its communications interface **98** and the network **90**, representing a desired ESS charge setpoint that has been determined by the ESS controller **72**. In response to such signals representing the ESS charge setpoint, block **230** directs the processor circuit to store a corresponding value in the ESS setpoint register **148**. Block **230** then directs the processor circuit to copy the contents of the ESS setpoint register **148** to the desired charging current register **152**.

Block **240** then directs the processor circuit **50** to identify a desired current drain from the energy bus **42**. In this embodiment, the desired current drain represents the total electrical current that is to be drawn from the energy bus **42** while regenerative braking is in progress. Thus, in the present embodiment, the desired current drain includes the desired charging current for charging the energy storage system **62**, stored in the desired charging current register **152** of the RAM **124**. In the present embodiment, the desired current drain further includes any currents drawn by the other high voltage loads **74**, including the transformer **76**. To identify the desired current drain, in the present embodiment, block **240** directs the processor circuit **50** to receive a signal from the second current sensor **104** via the network **90**, representing the electrical current presently being drawn by the other high voltage loads **74**, as measured by the second current sensor **104**. Block **240** directs the processor circuit to store a value representing the measured drawn current in the other loads register **153** of the RAM **124**. Block **240** then directs the processor to add the contents of the desired charging current register **152** and the other loads register **153**, and to store the resulting sum in the desired current drain register **156**.

Block **250** then directs the processor circuit **50** to identify a maximum desired regenerative braking torque, in response to the total desired braking torque and the maximum available regenerative braking torque. In this regard, in the present embodiment, in order to prevent voltage and current spikes on the energy bus **42** which would potentially damage the energy storage system **62**

or one or more of the other high voltage loads **74**, it is desirable to control the respective energy contributions of the regenerative braking system **46** and of the energy generating device **44**, to prevent their respective energy contributions from exceeding a total desired energy contribution. In this

5   embodiment, the total desired energy contribution is equal to the desired current drain value stored in the desired current drain register **156**. In order to control these energy contributions, a maximum desired regenerative braking torque value is identified and a corresponding desired output of the energy generating device is also identified, as discussed in greater detail below. The

10   actual regenerative braking torque is then increased as quickly as possible (by increasing the setpoint or present desired regenerative braking torque) to the maximum desired regenerative braking torque while preventing the contributions of the energy generating device and of the regenerative braking system from exceeding the total desired energy contribution.

15   In this embodiment, to identify the maximum desired regenerative braking torque, block **250** first directs the processor circuit **50** to calculate a torque equivalent of the desired current drain value stored in the desired current drain register **156**. To calculate the torque equivalent, block **250** first directs the processor circuit to receive signals from the regenerative braking system

20   **46** via the network **90** representing the rotational speed R (in radians per second) of the traction motors **54** and **56**, and to store this value in the traction motor properties register **142**. Block **250** then directs the processor circuit to receive signals from the voltage sensor **97** via the network **90** representing a measurement of the present voltage V on the energy bus **42**, and to store a

25   value representing the present energy bus voltage V in the energy bus voltage register **154**. Block **250** then directs the processor circuit to multiply the voltage value stored in the energy bus voltage register **154** by the current value stored in the desired current drain register **156**, to produce a corresponding power value P. The processor circuit is then directed to use

30   this power value P and the traction motor rotational speed value R stored in

the traction motor properties register **142** to locate and address a corresponding record in the second traction motor efficiency look-up map **135**. Upon locating the corresponding record, block **250** directs the processor circuit to copy an efficiency value *E* stored in an efficiency field (not shown) of the addressed record in the efficiency look-up map, to the traction motor efficiency register **155** in the RAM **124**. Block **250** then directs the processor circuit to calculate the torque equivalent of the desired current drain as follows:

$$\tau = \frac{VI}{RE}$$

wherein:

τ =   the torque equivalent of the desired current drain;

V =   the present DC voltage on the energy bus **42**, stored in the energy bus voltage register **154**;

I =   the desired current drain, stored in the desired current drain register **156**;

R =   the rotational speed of the traction motors, stored in the traction motor properties register **142**; and

E =   the traction motor efficiency value stored in the traction motor efficiency register **155**.

Block **250** directs the processor circuit to store the calculated torque equivalent in the torque subfield **157** of the desired current drain register **156**.

Block **250** then directs the processor circuit **50** to identify the maximum desired regenerative braking torque, by setting the contents of the maximum desired regenerative braking torque register **158** equal to the lesser of: the total desired braking torque value stored in the total desired braking torque register **140**; the maximum available regenerative braking torque value stored in the maximum available regenerative braking torque register **144**, and; the

torque equivalent of the desired current drain, stored in the torque sub-field **157** of the desired current drain register **156**. Thus, the maximum desired regenerative braking torque is not permitted to exceed the torque equivalent of the desired current drain, nor is it permitted to exceed either the total

5   desired braking torque or the maximum available regenerative braking torque.

Block **260** then directs the processor circuit **50** to set a desired power output of the energy generating device **44**, in response to the maximum desired regenerative braking torque identified above at block **250**. More particularly, block **260** configures the processor circuit to set the desired power output by

10   setting a desired current level of the auxiliary power unit **64** of the vehicle **48**.

In this regard, in the present embodiment, as noted, it is desirable to prevent the energy contributions of the regenerative braking system **46** and the energy generating device **44** from exceeding the total desired energy contribution, which in this embodiment is the contents of the desired current

15   drain register **156**. If this necessitates a reduction in the power supplied by either the energy generating device **44** or the regenerative braking system **46**, then it is preferable to reduce the power supplied by the energy generating device **44**, while permitting the regenerative braking system **46** to provide the maximum desired regenerative braking current to the energy bus **42**.

20   Conversely, however, if the sum of energy contributions of the energy generating device and the regenerative braking system would not exceed the total desired energy contribution, it is not necessary to reduce the output of the energy generating device.

In addition, in the present embodiment, when the energy supply routine **128** is

25   first executed in response to a new braking signal detected at block **200**, it is desirable to proactively control the energy supplied by the energy generating device **44** to the energy bus **42**, before the regenerative braking system **46** first begins supplying energy to the energy bus, in order to proactively prevent the total energy on the energy bus from exceeding the total desired energy

contribution, in contrast with conventional reactive systems which typically do nothing until after an over-voltage condition is already in the process of occurring. Thus, in this embodiment, on the first execution of the energy supply routine **128**, block **260** configures the processor circuit **50** to commence the controlling of the energy supplied by the energy generating device **44** no later than a time at which the regenerative braking system **46** of the vehicle **48** commences supplying energy to the energy bus. More particularly, in this embodiment the first execution of block **260** configures the processor circuit to commence controlling such energy supplied by the energy generating device before commencement of the supply of regenerative braking energy to the energy bus, as the latter does not occur until the first execution of block **270** (discussed below) in the present embodiment.

In view of the foregoing, in this embodiment, to set the desired power output of the energy generating device **44**, block **260** first directs the processor circuit **50** to receive signals from the auxiliary power unit **64** via its communications interface **94** and the network **90**, the signals representing a present desired current level of the auxiliary power unit **64**. More particularly, in this embodiment, the present desired current level includes an APU setpoint that has been established by a separate energy management controller (not shown, not part of this invention). Alternatively, if desired, such signals may be received from the energy management controller via the network **90**. Block **260** directs the processor circuit to store a value corresponding to the received signals in the desired APU power output register **160**.

Block **260** then directs the processor circuit **50** to calculate a current equivalent of the maximum desired regenerative braking torque value stored in the maximum desired regenerative braking torque register **158**.

To calculate the current equivalent, it will be recalled that at block **250** above, the processor circuit was directed to receive signals from the regenerative braking system **46** via the network **90** representing the rotational speed R (in

radians per second) of the traction motors **54** and **56**, and to store this value in the traction motor properties register **142**, and likewise, the processor circuit was directed to receive signals from the voltage sensor **97** via the network **90** representing a measurement of the present voltage V on the energy bus **42**, and to store a value representing the present energy bus voltage V in the energy bus voltage register **154**. Due to the negligible time elapsed between execution of block **250** and block **260**, these values R and V will generally continue to be sufficiently accurate that re-measuring these values is unnecessary. Alternatively, however, these values may be re-measured and stored at block **260** if desired. Block **260** then directs the processor circuit to use the maximum desired regenerative braking torque value τ stored in the maximum desired regenerative braking torque register **158**, and the traction motor rotational speed R stored in the traction motor properties register **142**, to locate and address a corresponding record in the first traction motor efficiency look-up map **134**. Upon locating the corresponding record, block **260** directs the processor circuit to copy an efficiency value E stored in an efficiency field (not shown) of the addressed record in the efficiency look-up map, to the traction motor efficiency register **155** in the RAM **124**. Block **260** then directs the processor circuit to calculate the current equivalent of the maximum desired regenerative braking torque, as follows:

$$I = \frac{\tau RE}{V}$$

wherein:

$I =$ the current equivalent of the maximum desired regenerative braking torque;

$\tau =$ the maximum desired regenerative braking torque value stored in the maximum desired regenerative braking torque register **158**;

$R =$ the rotational speed of the traction motors, stored in the traction motor properties register **142**;

$E =$ the traction motor efficiency value stored in the traction motor efficiency register **155**; and

5    $V =$ the present DC voltage on the energy bus **42**, stored in the energy bus voltage register **154**.

Block **260** directs the processor circuit **50** to store the calculated current equivalent I in the current sub-field **159** of the maximum desired regenerative
10   braking torque register **158**.

Block **260** then directs the processor circuit **50** to set the desired current level of the auxiliary power unit **64** equal to the lesser of: the present desired current level of the APU, stored in the desired APU power output register **160**, and; the desired current drain value stored in the desired current drain register
15   **156** minus the current equivalent of the maximum desired regenerative braking torque stored in the current sub-field **159**. Block **260** directs the processor circuit to store this new desired current level in the desired APU power output register **160**, and to transmit control signals via the network **90** to the interface **94** of the auxiliary power unit **64**, to specify the new desired
20   current level or current setpoint for the auxiliary power unit **64**. In this embodiment, the interface **94** of the auxiliary power unit includes a controller (not shown) that receives these signals from the processor circuit specifying the current setpoint, monitors the actual current output of the auxiliary power unit, and adjusts the actual current output of the APU to cause it to conform to
25   the specified current setpoint. Thus, it will be appreciated that if, prior to execution of block **260**, the present desired current level or current setpoint of the APU plus the current equivalent of the maximum desired regenerative braking torque would exceed the total desired energy contribution (in this embodiment, the contents of the desired current drain register **156**), then the
30   effect of block **260** is to cause the processor circuit to reduce the power

supplied by the energy generative device to the energy bus by reducing the desired current level of the APU, in order to make room for the full current equivalent of the maximum desired regenerative braking torque on the energy bus **42**, without the total energy exceeding the desired current drain from the energy bus. Conversely, however, if, prior to execution of block **260**, the sum of the present desired current level or setpoint of the APU plus the current equivalent of the maximum desired regenerative braking torque would not exceed the total desired energy contribution, then the desired current level or current setpoint of the APU is effectively unchanged.

Block **270** then directs the processor circuit **50** to set a present desired regenerative braking torque of the regenerative braking system **46** of the vehicle **48**, in response to the maximum desired regenerative braking torque and the power supplied by the energy generating device **44** to the energy bus **42**. In this regard, it will be appreciated that if the desired current level of the auxiliary power unit **64** was reduced at block **260**, there may be a slight delay while the auxiliary power unit output drops from its previous level to its new desired current level as established by the processor circuit at block **260**. During this delay time, it is desirable not to set the present desired regenerative braking torque equal to the maximum desired regenerative braking torque, as this may result in a voltage spike and a current spike on the energy bus **42** exceeding the desired current drain, during the delay time in which the auxiliary power unit has not yet dropped its output to the desired level. To prevent such spikes from occurring and potentially damaging the energy storage system **62** and the other high voltage loads **74**, block **270** effectively configures the processor circuit **50** to increase the power supplied by the regenerative braking system **46** to the energy bus **42**, while reducing the power supplied by the energy generating device **44** to the energy bus (the latter reducing commencing when the processor circuit set the present desired current level of the APU **64** at block **260** above, and continuing through the delay during which the APU reduces its output to this new desired

current level). More particularly, in this embodiment block **270** directs the processor circuit to increase such power by increasing a regenerative braking torque applied by the regenerative braking system **46** until a desired regenerative braking torque, namely the maximum desired regenerative braking torque, is achieved.

To achieve this, in the present embodiment, block **270** directs the processor circuit **50** to set the present desired regenerative braking torque in response to the maximum desired regenerative braking torque and the power presently being actually supplied by the auxiliary power unit **64** to the energy bus **42**. More particularly, block **270** directs the processor circuit to receive signals from the first current sensor **96** via the network **90**, representing the actual current presently supplied by the auxiliary power unit **64** to the energy bus **42**. Block **270** then directs the processor circuit to store a value representing this actual APU current in the actual APU power output register **162**. Block **270** then directs the processor circuit to set the present desired regenerative braking torque equal to the lesser of: the maximum desired regenerative braking torque value stored in the maximum desired regenerative braking torque register **158**, and; a torque equivalent of the desired current drain value stored in the desired current drain register **156** minus the actual current supplied by the energy generating device to the energy bus stored in the actual APU power output register **162**. This torque equivalent of the difference between the desired current drain and the actual current supplied by the APU is calculated in a manner similar to that discussed above in connection with block **250**. In the present embodiment, this calculation of the present desired regenerative braking torque at block **270** is subjected to the further constraint that the present desired regenerative braking torque is not permitted to be less than zero (this could occur, for example, in the event that the actual current supplied by the APU to the energy bus already exceeds the desired current drain). Block **270** directs the processor circuit to store the present desired regenerative braking torque value in the present desired

regenerative braking torque register **164**. Block **270** further directs the processor circuit to transmit control signals via the network **90** to the interface **100** of the regenerative braking system **46**, to cause the traction motors **54** and **56** to apply a regenerative braking torque to the drive wheels **58** and **60** equal to the torque value specified in the present desired regenerative braking torque register **164**. In this embodiment, the interface **100** of the regenerative braking system includes a traction motor controller (not shown) that receives these signals from the processor circuit specifying the present desired regenerative braking torque, monitors the braking torque presently applied by the traction motors, and adjusts the braking torque applied by the traction motors to cause it to conform to the specified present desired regenerative braking torque.

It will be appreciated that blocks **260** and **270** effectively direct the processor circuit **50** to reduce power supplied by the energy generating device **44** to the energy bus **42**, while increasing power supplied by the regenerative braking system **46** to the energy bus. Block **270** effectively configures the processor circuit to increase the regenerative braking torque applied by the regenerative braking system **46** until a desired regenerative braking torque, namely the contents of the maximum desired regenerative braking torque register **158** is achieved, while at the same time the power supplied by the auxiliary power unit **64** is being reduced to its new output level established at block **260**.

Block **280** then directs the processor circuit **50** to set a friction braking torque of the friction braking system **80** of the vehicle **48**. More particularly, block **280** directs the processor circuit to set the friction braking torque equal to a difference between the present desired regenerative braking torque and the total desired braking torque. To achieve this, block **280** directs the processor circuit to subtract the contents of the present desired regenerative braking torque register **164** from the contents of the total desired braking torque register **140**, and to store the resulting difference in the friction braking torque register **166**. If the resulting friction braking torque value is greater than zero,

block **280** directs the processor circuit to transmit control signals via the network **90** to the control interface **106** of the friction braking system **80**, to cause the friction braking system **80** to apply a frictional braking torque equal to that specified in the friction braking torque register **166** to the wheels of the vehicle **48**. In this regard, in the present embodiment the interface **106** of the friction braking system includes a friction brake controller (not shown) that receives these signals from the processor circuit specifying the required friction braking torque, monitors the friction torque presently applied by the friction braking system, and adjusts the braking torque applied by the friction braking system to cause it to conform to the specified required friction braking torque.

Following execution of block **280**, the processor circuit is directed back to block **200** as discussed above.

It will be appreciated that a number of advantages may flow from specific embodiments of the invention such as the second embodiment described above. For example, the second specific embodiment described above provides proactive avoidance of over-voltage conditions on the energy bus that would otherwise be potentially damaging to the energy storage system and to other electronic components in communication with the energy bus, such as the other loads. Thus, the effective service lifetimes of the energy storage system and of other electronic components of the vehicle are improved. Auxiliary power unit transients may be further minimized in situations where an opportunistic or fast charging strategy is selected. By reducing the output of the auxiliary power unit in order to accommodate a maximum amount of regenerative braking energy, vehicle efficiency is increased, with the result that fuel consumption and emissions by the auxiliary power unit are reduced. The use of friction brakes to complement the regenerative braking system serves to ensure that adequate braking torque is available, while transparently providing a predictable, constant and smooth brake feel to the operator, supplying the expected total braking torque in

response to brake actuation, irrespective of the precise proportions of regenerative and friction braking. At the same time, however, maximizing the amount of regenerative braking also serves to reduce friction brake wear, by reducing the frequency and required torque of friction braking events, thereby reducing maintenance costs of the vehicle. However, although such advantages flow from the second specific embodiment of the invention described above, it will be appreciated that not all embodiments of the invention necessarily provide these advantages.

More generally, while specific embodiments of the invention have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.